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Small-hydropower integration in a multi-purpose dam-bridge for sustainable urban mobility

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ABSTRACT

This paper describes a project for the integration of mini-hydro renewable energy in the trolleybus traction lines and in the electric battery operated mini-buses. Given the nearby hydropower resource of the Mondego river, a study was carried out in order to assess the technical and economical feasibility of hydropower production at an already existing multi-purpose mobile dam-bridge, located in Coimbra, Portugal, where a very low head run-of-river small-hydropower plant can be installed. As the main civil works have already been done, the hydropower installation costs are significantly reduced because the investment mainly resumes to hydro-mechanical, hydro-electrical and electrical equipment, with expected low hydraulic structure impact, as well as minimum environmental and visual impacts. The optimization of the hydroelectric production takes into account the seasonal water supply demands for agricultural, municipal and industrial use, the water discharges from the upstream reservoir system of Aguieira–Raiva–Fronhas, the very low head turbines state of the art technology, the physical constraints of the structure and the special feed-in tariff for renewable power plants. The small-hydropower plant, coupled with the electric public urban transportation fleet, will contribute to a sustainable clean mobility concept, reducing electric grid transportation losses by decentralized production and reducing greenhouse gases emissions, contributing to urban air quality improvement and to the Kyoto Protocol fulfillment.

Contents

Abbreviations: UNFCCC, United Nations Framework Convention on Climate Change; EU, European Union; GHG, Greenhouse gases; EC, European Commission; CO_2, Carbon dioxide; SMTUC, Coimbra Municipality Urban Transport Services; AHM, Hydraulic Mondego Development; INAG, National Water Institute.

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1. Introduction

As a party of the Kyoto Protocol of the UNFCCC, Portugal, in accordance to the EU burden-sharing commitment, agreed on the objective of limiting the growth of GHG emissions to 27% of the 1990 levels, during the period of 2008–2012. The EU, as a whole, agreed with an 8% reduction of GHG emissions. More recently, in December 2009, during the UN climate summit held in Copenhagen (Denmark), the negotiations between developed and developing countries failed and the summit ended without new target goals for GHG emissions cuts.

In order to achieve Kyoto emissions reduction target goals, the EC in March of 2007, established several key targets, known as the 20/20/20, for the year of 2020:

- Reduction of at least 20% of GHG emissions.
- 20% share of renewable energies in the total EU energy consumption.
- 20% energy saving through improvements in the energy efficiency.

The EC in order to achieve these targets, decided to develop legislative and non-legislative frameworks to cut CO_2 emissions, reduce oil dependence and also improve mobility inside European cities supporting and financing several programs like CIVITAS – CIty, VITAlity and Sustainability. The CIVITAS program “for better and cleaner transport in cities” included the Portuguese city of Coimbra in the 3rd phase of the main project, the CIVITAS PLUS, in the MODERN – MObility, Development and Energy use ReductioN – Project, supported by the 7th RTD Framework Program of the EC. One of the main measures for the city of Coimbra is the feasibility study of the implementation of a small hydro power plant in the already existing Coimbra dam-bridge.

Beyond the concept of sustainable urban mobility, the measure’s main goal is the production of electricity in order to satisfy the electricity consumption of the electric traction lines of the trolleybuses and electric mini-buses of the Coimbra’s urban public transportation fleet. From 2000 to 2008, the average consumption of the trolleybuses traction lines was about 760 MWh. The electric minibus provides a transport service for the historical zone of Coimbra, characterized with high slopes and narrow streets, and from 2005 to 2007, the average consumption was about 145 kWh per 100 km [1]. Each mini-bus travels an average distance of 45 km per day, so the total electricity consumed by the electric fleet of the public transportation system can be approximated to 800 MWh/year [2]. When compared to equivalent diesel buses, the electric trolleybuses and mini-buses present some advantages like: non-local emissions,[1] gases emissions reduction in a global scenario, higher performance and overload capacity, low maintenance, low noise emission, longer life and lower operation costs.

According to the Portuguese National Inventory Report on GHG, in 2006, total Portuguese GHG emissions without land-use, land-use change and forestry were estimated at about 83.2 Mt CO_2 equiv. representing an increase of 40.7% compared to 1990 emissions levels. Energy industries and transports are by far the most important sectors, accounting 51% of total emissions in 2006 [3]. According to the Portuguese National Climate Changes Program, from 1990 to 2005, emissions in the energy industries[2] and transportation subsectors increased respectively about 60% and 104% [4]. This situation reflects the country heavy dependence and demand increase in the past few years on fossil fuels, for electric energy production and transportation and the necessity of changes regarding the energetic policies.

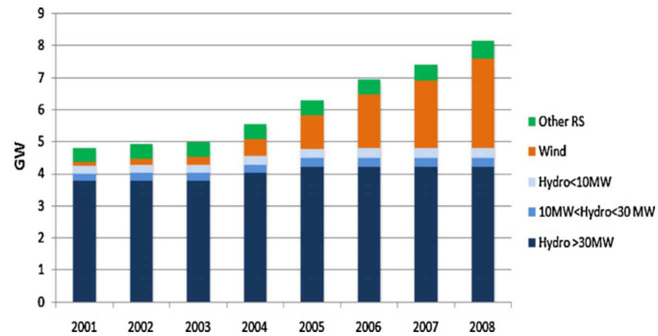


Fig. 1. Portuguese Mainland-installed power of renewable sources [5].

The Portuguese electric production system suffered in the last few years significant positive changes in order to reduce the emission of pollutant gases. In the thermal production system, there was an increase of the efficiency, especially with the integration of combined-cycle natural gas and cogeneration power plants. In the pollutant coal power plants, scrubbers and electrostatic precipitators were installed in order to reduce gases and particles emissions. Wind power had by far the largest increase in the production mix, since 2003. Wind power and hydropower represented in 2008, respectively 38.3% and 47.8% of the total renewable production and the share of renewable sources represented 27.8% of total production [5]. Fig. 1 presents the evolution of renewable energy installed capacity in the Portuguese electric production mix from 2001 to 2008.

The largest improvement was, with no doubt the wind power, with an average yearly growing rate of 58%, from 2001 to 2008. Hydropower schemes with capacity above 30 MW, between 30 and 10 MW and less than 10 MW had a low average yearly growing rate of respectively 1.6%, 2.3% and 3.0% from 2001 to 2008. Solar power plants installed capacity also increased from 4.8 MW in 2006 to 38.1 MW in 2008, but is not significant in the whole production.

In 2007, the Portuguese National Government established the commitment of upgrading the electrical renewable share, from 39 to 45% of all electricity consumption by the end of 2010. To the fulfillment of this target, the most important objectives defined for various renewable energy sources were [6]:

- *Wind power*: To increase installed capacity, by the year 2012, to a total 5100 MW (600 MW by equipment upgrade).
- *Hydropower*: Reinforce of capacity of current hydroelectric facilities, to achieve 5557 MW of installed power in 2010.

More recently, in 2009, the Portuguese Government decided to upgrade these objectives to a medium term perspective [7]:

[1] Electric motor vehicles emissions are associated with electric production system emissions.

[2] Energy industries include the production of electric energy and heat, oil refineries and other small energy industries (excluding fugitive emissions).

- *Wind power*: To increase installed capacity, by the year 2020, to a total 8500 MW with off-shore exploration and micro-wind power utilities.
- *Hydropower*: Implementation of the National Program of Dams with Large Hydropower Potential. For this purpose, Portugal identified and defined priorities for the investments in the hydropower sector for the period of 2007–2020 in the National Program of Dams with Large Hydropower Potential. In 2020, the hydropower capacity is foreseen to be about 7000 MW increasing the hydropower generating capacity potential from 46 to 70%. The first 10 new investments (7 with reversible groups), to be carried out until by the end of 2010, will increase the reservoir capacity in 1266 km^3, power capacity in 1096 kW and will produce, in an average hydrological year, about 1632 GWh [8]. Promotion and development of small hydropower, aims to increase by 50% the actual capacity. Another objective is the maximization of the connection and joint operation of wind with hydropower reversible storage capacity schemes.

In the transportation sector, road traffic largely dominates all the transport systems, especially because of the strong investment in road infrastructures and the increase of private vehicles fleet in the 90 s. This contributed to the growth of GHG emissions in the sector. In 2005, it was estimated that the transport in private cars was responsible for more than half of the energy consumption and the GHG emissions of the transportation sector. More than 60% of these values were referred to urban and suburban travels [4]. These last values show the potential and necessity of measures to improve energy efficiency and mobility, especially inside cities. Electric vehicles for private and public transportation are seen as the future to achieve sustainable mobility improving significantly the air quality inside cities.

The SMTUC lately began an increasing investment program in the electric fleet. In 2009, it was inaugurated a new rectifying substation for the traction line service and a new and more efficient trolleybus was bought. Complementing electric vehicles with a clean source of energy, such as hydropower using an already existing dam, can provide the solution for air quality improvement inside Coimbra city, increasing the global efficiency of the public transports, decrease fossil fuel dependence and also reducing operational costs. The production of clean and renewable electric energy, will also contribute to the national objective of 39% share of renewable sources in the national electric production system, established in the European Directive 2001/77/CE.



Fig. 2. Satellite view of Coimbra dam-bridge [Google Earth].

2. The Coimbra dam-bridge

2.1. Introduction

The dam-bridge is located in the Mondego river on the northwest of Coimbra 1340 m downstream of the Santa Clara bridge and 340 m upstream the railway bridge (see Fig. 2). The city of Coimbra is located in the centre region of Portugal and the municipality has about 150,000 inhabitants.

The Fig. 3 presents the location of the Coimbra dam-bridge, and the main characteristics (total capacity, power capacity and average annual production) and locations of the major large hydroelectrical power stations in the Mondego basin. The projected Girabolhos power plant, presented in the National Program of Dams with Large Hydropower Potential, is already here presented.

The basin of the Mondego river, which has its origin in the Serra da Estrela Mountain, nearly 1450 m high, has a total area of 6644 km^2 and it is located in the central region of Portugal. The Mondego river is 234 km long up to the Atlantic Ocean at Figueira da Foz. Besides the main river course, there are 5 main tributaries, the Pranto, Arunca, Ceira, Alva and Dão rivers, referred from downstream to upstream.

The most important reservoirs located upstream the Coimbra dam-bridge are those in the multi-purpose system of Aguieira–Fronhas–Raiva. The system has a total capacity of 360 MW and an average production of 250 GWh/year. The Fronhas reservoir has no generation capacity but it is used to divert water from the Alva river to the Aguieira reservoir through a tunnel of 8.2 km long. The Aguieira dam, besides the production of electric energy and flow regulation, has a strong social–economical impact in the

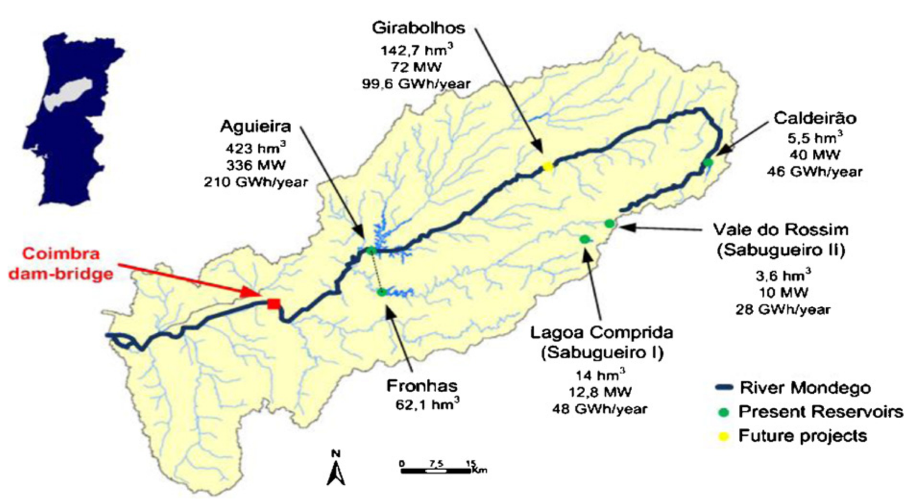


Fig. 3. Basin of Mondego with Coimbra dam-bridge and large reservoirs locations.

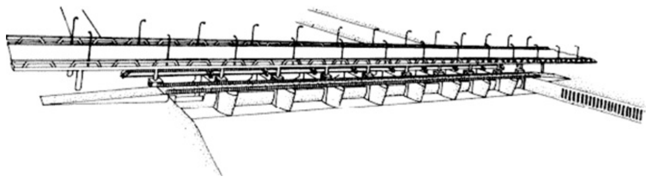


Fig. 4. Perspective view of the Coimbra dam-bridge [10].

central region, due to municipal and industrial water supply, agricultural irrigation and touristic and recreational activities. Located downstream of Agueira dam, is the run-of-river Raiva dam, with a storage capacity of 24.11 hm^3. The Aguieira hydropower scheme is equipped with reversible groups. Most of the times it produces electric energy in the peak consumption hours, discharging the water to the Raiva dam. During the night, in the low consumption periods, the water accumulated in the Raiva dam is pumped again to the upstream reservoir of the Aguieira dam [9]. Besides this functioning mode, the Aguieira and Raiva dams also produce energy using the water that must be definitely released to downstream.

2.2. Main characteristics

Table 1 presents the Coimbra dam-bridge main characteristics.

The dam is clearly a run-of-river scheme. The storage level capacity of 0.62 hm^3 is negligible when compared with the annual integral average affluent flows of about 2300 hm^3. The dam-bridge project defined it as a mobile type dam with 9 spillways. Each spillway is separated from the others by pillars with 3 m thick [11]. Fig. 4 presents a perspective view of the Coimbra dam-bridge.

The centre of the spillways, for maintenance purpose, can be isolated by installing 2 vertical lift gates between the pillars, located upstream and downstream of the gates (see Fig. 5). Each vertical lift gate has an approximate weight of 8 tonnes and they are moved with two cranes with a maximum lift capacity of 10 tonnes. Fig. 5 presents the profile view of the Coimbra dam-bridge.

The downstream riverbed is only 1 meter below the upstream riverbed. The full storage water level (NPA in Fig. 5) and the minimum exploration levels are respectively 18 m and 17.5/17.3 m. The dam has a very low head [10].

Regarding the hydro-mechanical equipment, the radial gates have a length of 15.4 m, 4.5 m height and a curvature radius of 8.0 m. The radial gates installed next to the river margins are equipped with top flap gates, for floating debris discharge, with a length of 8.6 m and 1.4 m height [11].

2.3. Actual exploration and discharge control

The Coimbra dam-bridge is integrated in the AHM. In addition to its interesting landscape and recreational function of the water mirror it has the following functions:

- Adjust the amount of ecological flow discharge.
- Store capacity of water for the deviation of flows mainly for irrigation proposals.
- Store capacity for industrial and municipalities' water supply.

The outflow to the dam-bridge have a strong irregularity throughout the year. The influent and outflow to the dam-bridge are strongly influenced by the discharges in the Aguieira–Raiva–Fronhas system which arrive the dam-bridge only after a few hours. Three main situations were identified:

- In the wettest months (winter), for the situation of full discharge for electric energy production in Raiva dam (about 160 m^3/s), and eventually in the situation of considerable discharges from its floodgates, the inflows to the Coimbra dam-bridge will be strongly conditioned by the total volume discharged in Raiva, but also by the non controlled flows in the Fronhas dam and the contribution of the Ceira River upstream the Portela area. In some extended periods of extreme rainfall, inflow to the dam-bridge can get close to the centenary flow (2000 m^3/s) [10].
- In an average situation of energy production in Raiva, there may be considerable variations throughout the day in the influent flows to the dam-bridge, from 10 m^3/s to 160 m^3/s.
- In the driest months (summer), the inflow to the dam-bridge will be much reduced, at around 5 m^3/s to 20 m^3/s and controlled by the discharges in Raiva. The analysis of the monthly average inflows and discharged volume of water by the floodgates, in the last 21 years, provide more information regarding the secondary channels water consumption throughout the year.

It can be seen at Fig. 6 that, in the wettest months, the amount of water discharged by the spillways is very close to the inflows, due to the low storage capacity of the reservoir. In the dry months, the average inflow volume is very low when compared to the wettest months. About half of this inflow volume is diverted for the

Table 1
Coimbra dam-bridge characteristics [10].

General data		Hydrological characteristics	
Owner	INAG (National Water Institute)	Basin	Mondego
Year of project/year of conclusion	1978/1981	Total basin area	4950 km^2
Project	*Hidroprojecto*	Average annual precipitation	1230 mm
Location	Mondego river	Annual integral average affluent flows	2333 hm^3
Reservoir characteristics		**Dam characteristics**	
Submerged area at top water level	92.5 ha	Type	Mobile dam
Total reservoir capacity	1.60 hm^3	Maximum height above foundation	39.2 m
Normal operating reservoir capacity	0.62 hm^3	Height above terrain	6.2 m
Non-available capacity (dead storage)	0.98 hm^3	Crest elevation	22 m
Full storage water level	18 m	Crest length	202.4 m
Maximum upstream level (flood conditions)	19 m	Foundation type of soil	Loam
Minimum upstream level for exploration	17.3/17.5 m	Concrete volume	48,400 m^3
Spillway			
Location	In the main body of the structure	Number of spillways	9
Type of control	Radial gates	Maximum discharge	2000 m^3/s
Upstream bottom elevation	14.3 m	Energy dissipation mechanism	Hydraulic jump
Length between pillars	15.4 m	Number of Gates equipped with top flap gates (*volets*)	2

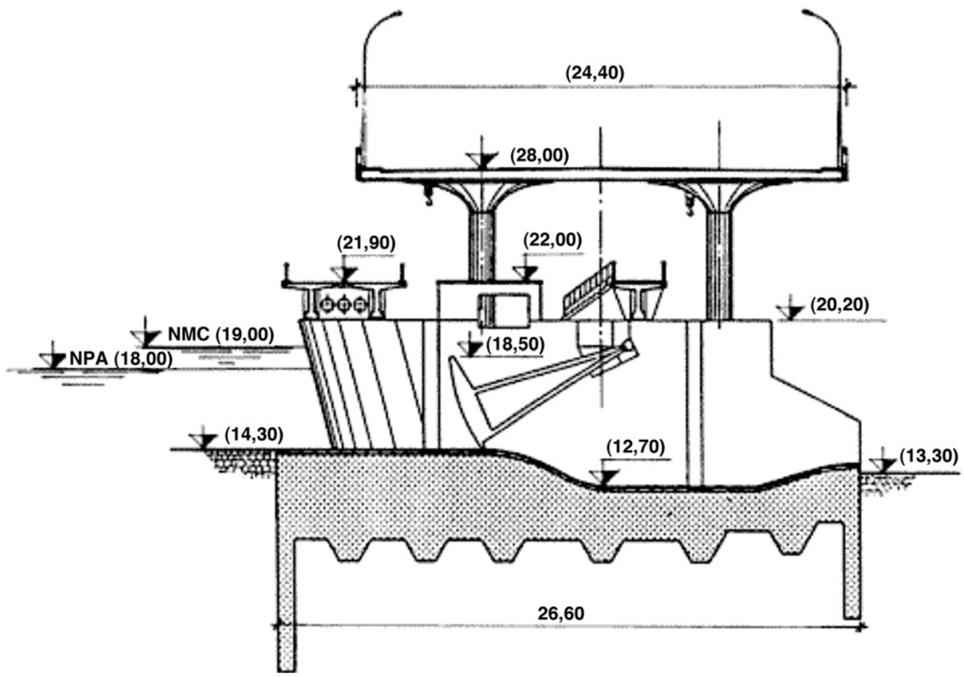


Fig. 5. Profile view of Coimbra dam-bridge [10].

secondary channels. In these periods, the Coimbra dam-bridge water diversion is mainly to assure agricultural irrigation. The flows discharged by the spillways are low and many times close to 4 m^3/s (ecologic flow). Typically in summer months the global volume diverted to the secondary channels is close to the global volume discharged by the spillways.

According to the main project, the spillways have a flow discharge of 1200 m^3/s, for a headwater level of 17.8 m. This level rises to 19 m (maximum level) for a flood flow of 2000 m^3/s [11]. Recently, some changes in the radial gates control algorithm were imposed, in order to prevent river bank flooding in some new upstream recreational areas. For this reason, the headwater levels must be kept below 17.5 m for inflows greater than 750 m^3/s. For low inflows, the headwater levels are kept between 17.5 m and 18 m. There are also opening and closing operating rules, defined in the main project, in order to avoid excessive erosion of the riverbed along the downstream end platform of the Coimbra dam-bridge.

2.4. Secondary channels

There are three water intakes for secondary channels located in the river banks next to the Coimbra dam-bridge. In the right margin is located the water intake for the right bank irrigation channel. In the left bank of the river are located the fish passage and the left bank irrigation channel (see Fig. 7).

2.4.1. Right bank channel

The right bank channel is made of concrete and has a trapezoidal transversal section. It was designed for a maximum flow of 25 m^3/s at full Coimbra dam-bridge storage level (NPA = 18 m). With a length of about 41 km from Coimbra to the municipality of Figueira da Foz, the channel is the main axis of the hydro-agricultural management of the Mondego Valley, responsible for the irrigation of a potential area superior to 12,500 ha, besides industrial and municipal water supply [13]. Fig. 8 presents the minimum, the average and the maximum values of water volumes derived to the right bank channel per month, based on data provided by the INAG covering the period from November 1987 to April 2009.

The highest water requirements for this channel happens during summer months, when the precipitation periods are typically reduced and the need for the irrigation of agricultural fields is more significant. The main crops are rice and corn representing about 90% of total agricultural fields in the Mondego Valley. The

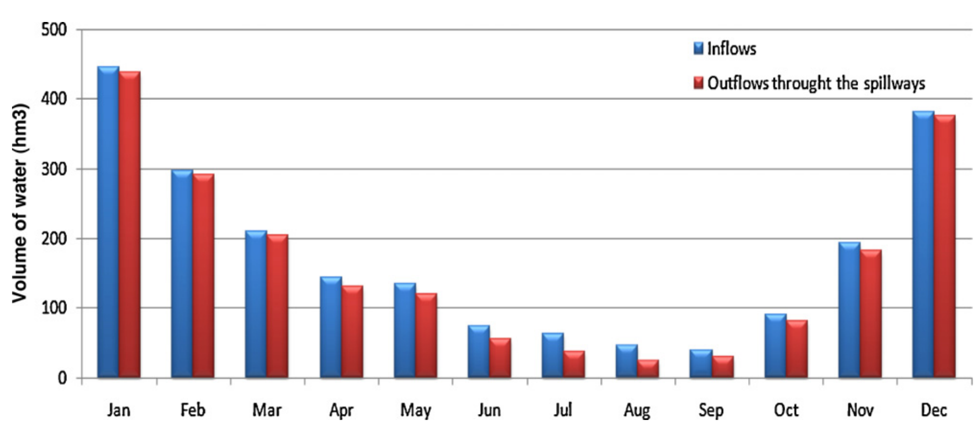


Fig. 6. Monthly average inflows and outflows through the spillways in the Coimbra dam-bridge.

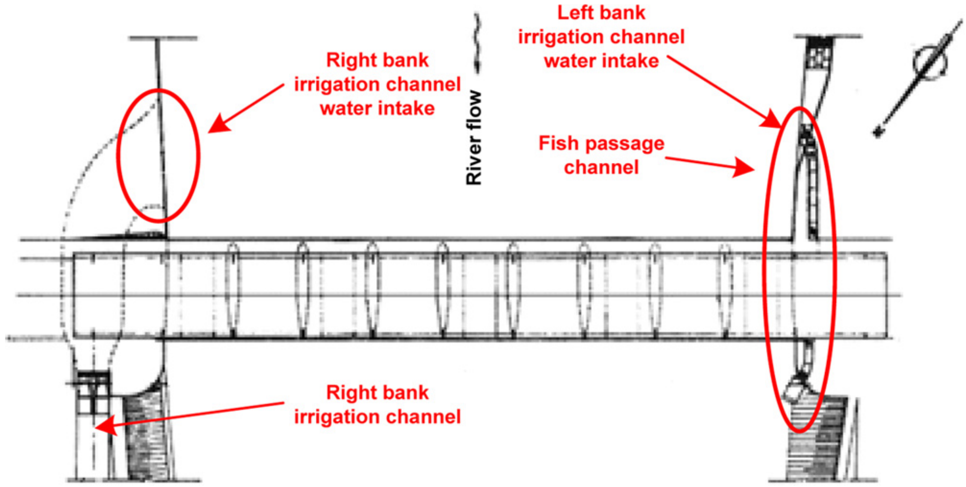


Fig. 7. Plan view of the Coimbra dam-bridge with fish passage and right bank irrigation channel (Adapted from [10]).

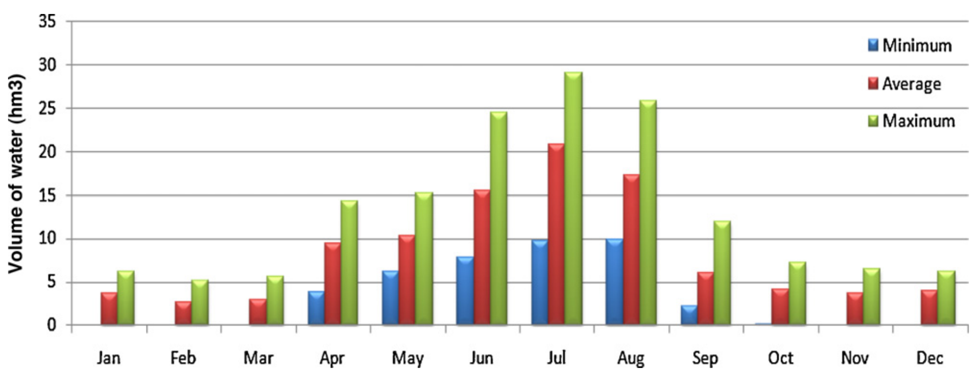


Fig. 8. Minimum, average and maximum monthly volume of water derived for the right bank irrigation channel.

cultivation of rice is particularly very demanding in water. In the rest of the months, the water demands are mainly for cellulose industries and municipalities (in 2001 the Figueira da Foz municipality consumption was close to 3 million m^3 per year) [13]. The maximum average daily flow was about 13 m^3/s.

2.4.2. Left bank irrigation channel

The left irrigation channel is designed for a maximum flow of 2 m^3/s. This channel is about 12 km long and ends in the municipality of Montemor-o-Velho, supplying water for the irrigation of agricultural fields with an approximate area of 700 ha [13]. Fig. 9 presents the minimum, the average and the maximum water volumes derived to this channel per month, based on data provided by the INAG, from January 1993 to December 2008.

The highest water consumption typically occurs in the summer months, with the peak consumptions in August and September. The maximum average daily flow was about 1.5 m^3/s.

2.4.3. Fish passage

The fish passage intake is located in the left margin and it was designed for a steady flow discharge of 1 m^3/s. The fish passage channel proved to be ineffective, disallowing the rise of species to upstream in the spawning period, so since 2004 a new project for a fish passage was promoted by the INAG. The construction was planned to start in the summer of 2009, but after several consecutive delays, it started in January 2010. The construction will take approximately 16 months. It will also have an observation room for the study of the species migration and will have an approximate total cost of 3.48 M€, with 2.61 M€ co-financed [14]. It will be only

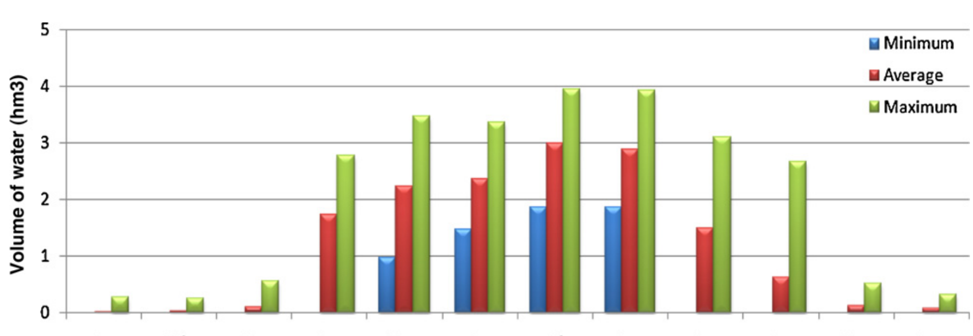


Fig. 9. Minimum, average and maximum monthly volume of water derived for the left bank irrigation channel.

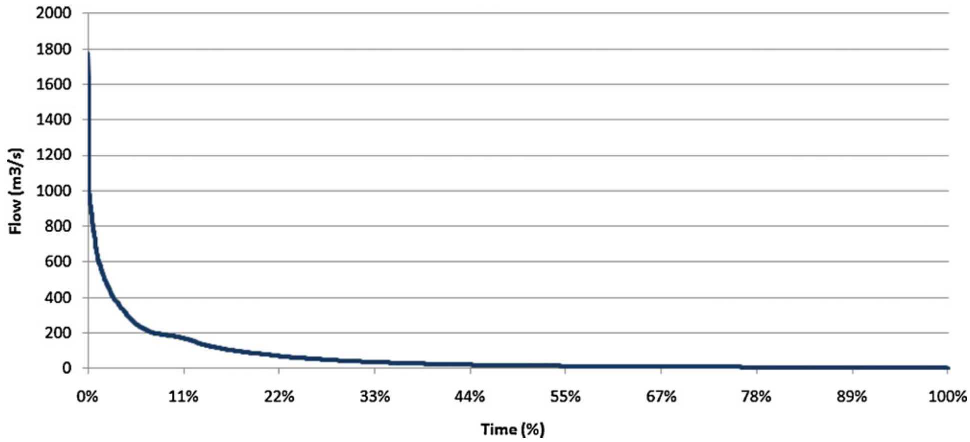


Fig. 10. Flow duration curve at the upstream area of the Coimbra dam-bridge.

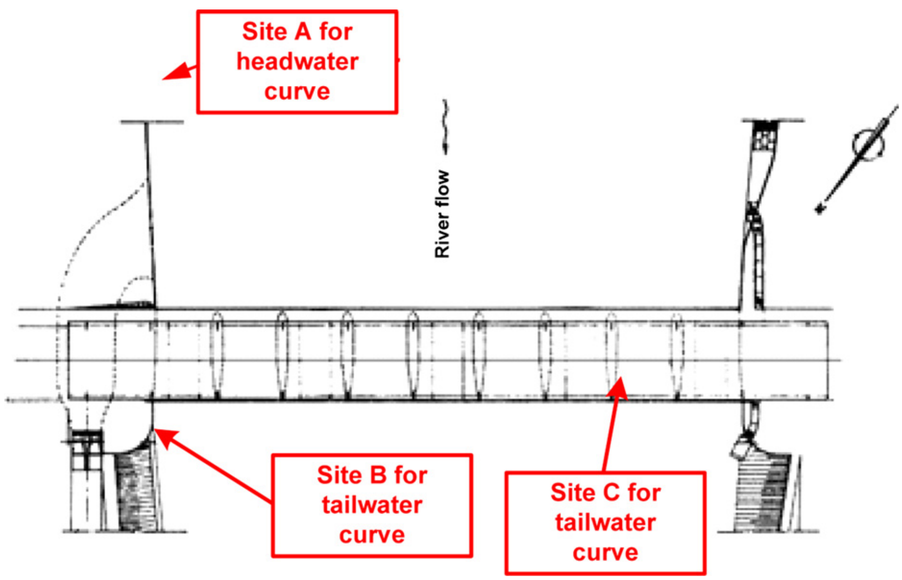


Fig. 11. Plan view of the Coimbra dam-bridge with the sites for headwater and tailwater curves.
(Adapted from [10]).

opened during the migration periods and will have an attraction flow around 2 m^3/s [15].

3. The Coimbra dam-bridge small hydro project

3.1. Primary considerations

Hydrological studies are required for the assessment of power capacity and estimation of electric energy production. An economical evaluation must also be carried out in parallel with these studies, to maximize production and revenues minimizing costs and impacts in the surrounding ecosystem. This feasibility study took into account the INAG hydro resources management constraints at the Coimbra dam-bridge.

The hydrological studies were facilitated with the installation, in the upstream area of the dam-bridge, of a hydrometric station, which enables since January 1987, inflow records. Since January 2006, hourly and instantaneous inflow, outflow and headwater and tailwater levels measurement capability was added. Based on these hydrometric records the power plant capacity and the electric energy production estimation will be developed.

3.2. Hydrological analysis

3.2.1. Flow duration curve

The hydrologic analysis provides the flow duration curve of the daily average flows, computed using a total of 8112 records from January 1987 to April 2009.[3] Fig. 10 presents this flow duration curve at the upstream area of the Coimbra dam-bridge. Data was obtained from [12].

3.2.2. Headwater and tailwater curves

The headwater and tailwater curves at sites A and B, respectively, were obtained from the hourly flows and levels provided by the automatic Coimbra dam-bridge hydrometric station, from January 2006 to April 2009.

An experimental estimation of the tailwater level at the end of the spillway, in site C, was also developed, because it will be considered the possibility of installing the turbines between the

[3] Flow records from October 12th, 2000 to November 24th, 2000 were removed from the analysis, because in that period the reservoir was empty for maintenance reasons.

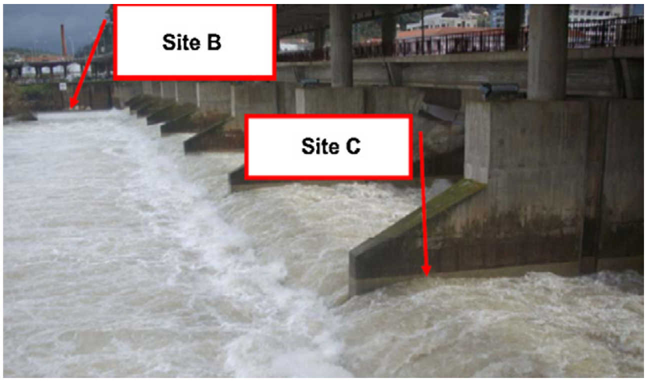


Fig. 12. Downstream view of the Coimbra dam-bridge locations of sites B and C for tailwater curves.

upstream and downstream extremities of the Coimbra dam-bridge. Figs. 11 and 12 show the headwater and tailwater sites considered in this study.

Fig. 13 presents the adopted headwater and tailwater curves in sites A and B, respectively. The headwater curve denotes the artificial behavior induced by human operation of the Coimbra dam-bridge.

The tailwater elevation in site C strongly influences the head, in cases where turbines are installed in the spillway. The tailwater level must be kept above minimum submergence level at turbine exit. For the StrafloMatrix units, a minimum submergence level of 14.6 m was considered. For VLH 3550-45-3.2 units, a minimum submergence level of 14.8 m was considered. The flap gate installed at the spillway end will ensure submergence condition in case of low flow. In case of high flows this flap gate will be lowered in order to maximize energy production. To investigate these hydraulic operational conditions, a scale model was built and tested. The laboratorial tests confirmed flap gate operational ability to control submergence and head. They also provided an empirical tailwater curve that was used in the energy production estimation computations. In Fig. 14, it is presented an example of a laboratorial scale model testing of submergence condition.

The Coimbra dam-bridge can discharge a flood flow of 2000 m^3/s, so each of the 9 spillways is able to discharge a maximum flow of 222.2 m^3/s.

3.3. Examples of minimum impact hydropower layouts

Due to urban constraints, the hydraulic circuit and powerhouse must be built with minimum civil construction works and minimum occupation of the river banks. The site geotechnical

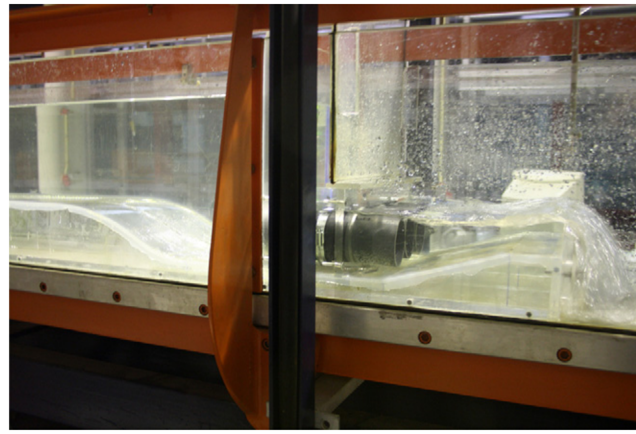


Fig. 14. Laboratorial scale model testing of submergence condition.

conditions also recommend minimum civil construction works because the bed rock is about thirty meters deep. So, new non classical approaches are being tested for the Coimbra dam-bridge feasibility study. The dam is meant to be equipped with recent technologies developed for very low head and suitable for small hydropower additions at existing facilities. As the main civil construction works in the structure have already been done, the hydropower installation costs will mainly consist in hydro-mechanical, hydro-electrical and electrical equipment. These recent technologies allow the installation of the turbine-generator units near the stop logs of the spillway, with a low hydraulic structure impact as well as minimum environmental and visual impacts.

From a broad analysis of commercially available very low head hydropower turbines, two main alternatives were chosen: the StrafloMatrix integrated turbine runner-generator rotor developed by ANDRITZ AG and the VLH turbo generator unit developed by the MJ2 Technologies S.A.R.L.

Both machines operate synchronously with the electric distribution system, in a close range of heads. However, they present considerable differences from geometrical and hydraulic point of view. In the following pages, two possible minimum impact layouts, using these technologies, will be presented.

Fig. 15 presents a schematic profile of the Coimbra dam-bridge equipped with a StrafloMatrix unit.

This layout consists of a vertical lift gate with embedded StrafloMatrix units that must be lifted in case of flood flow. In order to reduce total weight of the module, each of the integrated turbine runner–generator rotors can be lifted separately before the vertical gate with the embedded draft tubes is lifted. A flap gate is

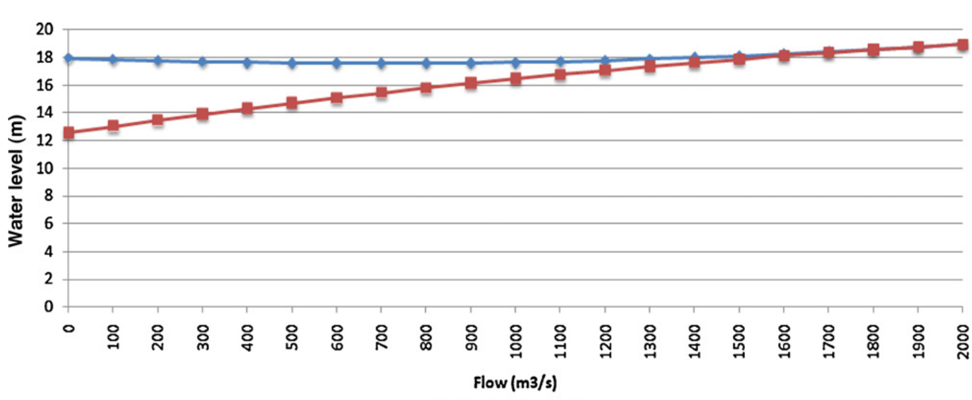


Fig. 13. Headwater and tailwater curves adopted in sites A and B, respectively.

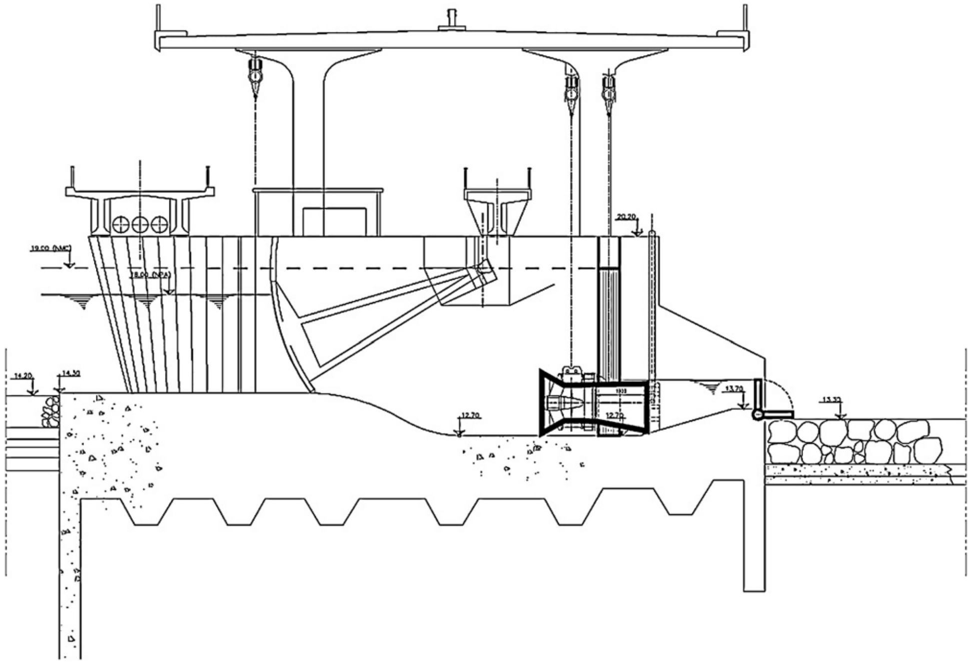


Fig. 15. Schematic profile of the Coimbra dam-bridge equipped with a StrafloMatrix unit.
(Adapted from [10]).

located at the exit of the spillway in order to insure the minimum submergence of the turbine in low flow conditions as well as to avoid situations of excessive head. The technical specifications of the StrafloMatrix unit, according to the supplier indicative data, are presented in Table 2.

A preliminary analysis lead to the conclusion that it is not desirable to occupy more that one of the nine spillways of the Coimbra dam-bridge, given that this hydraulic structure is intended to remain simple and highly available for flood flows discharge. In a single spillway a maximum of 6 StrafloMatrix units can be accommodated.

Fig. 16 presents a schematic profile of the Coimbra dam-bridge equipped with a VLH turbo generator unit.

This layout consists on the installation of inclined axial VLH turbo generator units, after previous radial gate removal. In case of flood flows each of the VLH turbo generator units can be removed by turning around its upper horizontal axis, using a crane. The flow through the turbines can be controlled by adequate regulation of turbine blades angle. However, a vertical maneuverable upstream lift gate should be installed to ensure turbine shutoff. A flap gate is located at the exit of the spillway in order to ensure the minimum submergence of the turbine in low flow conditions as well

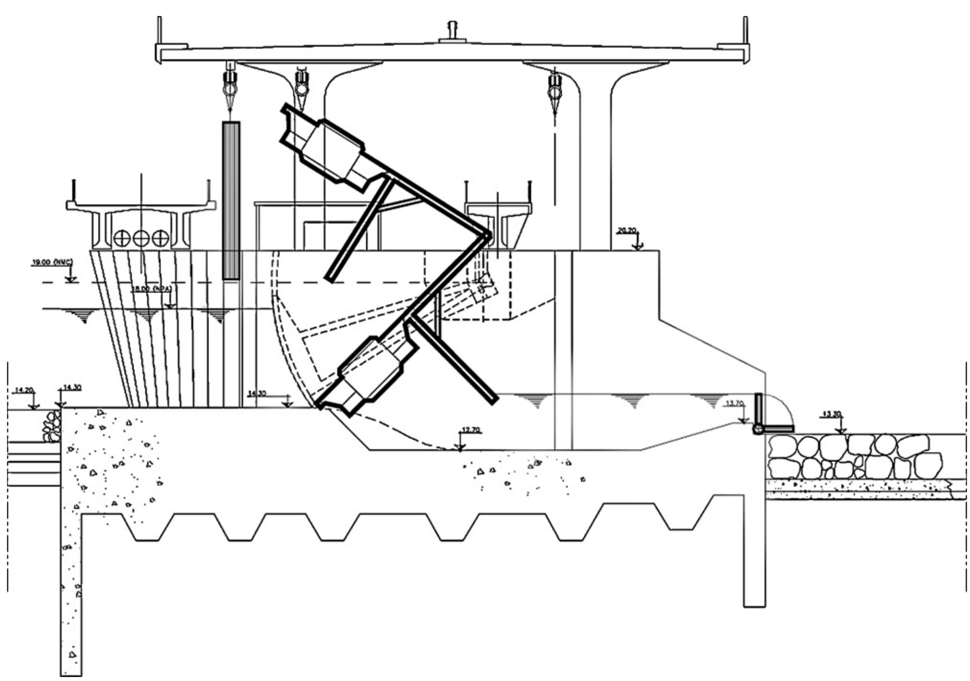


Fig. 16. Schematic profile view of the Coimbra dam-bridge equipped with a VLH turbo generator unit.
(Adapted from [10]).

Table 2
Indicative technical specifications of the StrafloMatrix unit.

Turbine	Horizontal axis Straflo type
Generator	Permanent magnet synchronous
Runner diameter	1320 mm
Number of runner blades	3
Synchronous speed	230.76 rpm
Runaway speed	460 rpm
Frequency	50 Hz
Turbine maximum output	310.7 kW
Discharge at P_{max}	12.37 m^3/s
Turbine minimum output	55 kW
Discharge at P_{min}	10.0 m^3/s
Gross head – maximum	4.3 m
Gross head – minimum	1.8 m

Table 3
Indicative technical specifications of a VLH 3550-45-3.2 unit.

Turbine	Inclined axial turbine
Generator	Permanent magnet synchronous
Runner diameter	3550 mm
Frequency	50 Hz
Turbine maximum output	389 kW
Discharge at maximum output	15.8 m^3/s
Discharge at minimum gross head	10.4 m^3/s
Gross head – maximum	3.2 m
Gross head – minimum	1.4 m

as to avoid situations of excessive head. The technical specifications of the VLH units, according to the supplier indicative data, are presented in Table 3.

In a single spillway, a maximum of three VLH 3550-45-3.2 units can be accommodated. These units replaced the initially considered VLH 4000-45-3.5, that were abandoned because they demanded too large demolition works.

3.4. Similar projects

A major limitation associated with the feasibility study of the hydropower addition to the Coimbra dam-bridge is the lack of "know-how" in this kind of facilities. However, it was possible to identify and visit two pilot projects: The Chievo project, in Italy, and the Millau project in France.

The Chievo project consists on the addition of a large vertical lift gate module with five embedded StrafloMatrix units, at the downstream end of a deactivated navigational lock located in the right river bank of the Adige river. The module accommodates in its interior some auxiliary equipment, the hydraulic circuit and the turbo generator units. Total installed capacity is 1.3 MW. A fish passage is located next to the module. The dimensions and weight of the module are considerable. A robust elevation system is required. There is a trash rack structure mounted at the upstream side of the module to collect debris. The trash rack cleaning machine travels on a bridge placed upstream the module. The module can be lifted in a matter of minutes using a 220 tonnes hoist, but previous upstream and downstream water level equalization is required. This project has many similarities with the Coimbra dam-bridge project.

The Millau project consists on the addition of a VLH unit at the end of a short channel built in the right downstream river bank of the deactivated pumping station of Troussy, on the Tarn river. In this demonstration site, a VLH DN 4500, with a nominal full output of 438 kW, nominal net head of 2.5 m and nominal flow of 22.5 m^3/s, is working since March of 2007. The fish passage is located in the opposite river bank. The VLH unit has shown a very smooth and vibration-less operation. A robust elevation system is not required because VLH unit is intended to turn around its upper frame horizontal axis. The unit has a self rotating automatic trash rack machine. Nevertheless an upstream grid is needed to protect against large debris. This project has many similarities with the Coimbra dam-bridge project.

3.5. Estimated hydropower production and revenues

Given a base of technical and administrative possible layouts, the optimum installed capacity can be found considering the balance between infrastructural costs and hydropower production revenue.

The feed-in tariff paid by the Portuguese national electric grid, depends on the average electric monthly power and on the electric energy produced. In order to evaluate hydropower production, two possible base layouts will be considered. The minimum downstream submergence elevation, the operation range (flows and heads), and simplified efficiency curves, were based on the preliminary information provided by the turbine suppliers. The production was obtained by computational simulation of the operation of the Coimbra dam-bridge in a spreadsheet. The INAG hydrologic series inflows from 1987 till 2009 and irrigation and water supply consumption patterns derived from INAG data covering the period, from January 2006 to April 2009, were used in this simulation.

The Table 4 presents estimated annual hydropower production, for several installed capacities, considering units similar to StrafloMatrix. Approximate efficiency curves, derived from indicative manufacturer data, were used. An extra efficiency reduction was considered to account for the undesirable non standard short draft tube.

The Table 5 presents estimated annual hydropower production for several installed capacities considering units similar to VLH.

Table 4
Estimated annual hydropower production for several installed capacities considering units similar to the StrafloMatrix units presented in Table 2.

Number of units	Total maximum output (MW)	Estimated annual energy produced (GWh)	Avoided CO_2 emissions (tonnes)[a]
1	0.31	1.0	370
2	0.62	1.5	555
3	0.93	1.8	666
4	1.24	1.9	703

[a] 370 g CO_2/kWh as stated in the Portuguese decree-law "Decreto-Lei n. ◦ 225/2007".

Table 5
Estimated annual hydropower production for several installed capacities considering units similar to the VLH units presented in Table 3.

Number of units	Total maximum output (MW)	Estimated annual energy production (GWh)	Avoided CO_2 emissions (tonnes)[a]
1	0.39	1.7	629
2	0.78	2.6	962
3	1.16	3.0	1110

[a] 370 g CO_2/kWh as stated in the Portuguese decree-law "Decreto-Lei n. ◦ 225/2007".

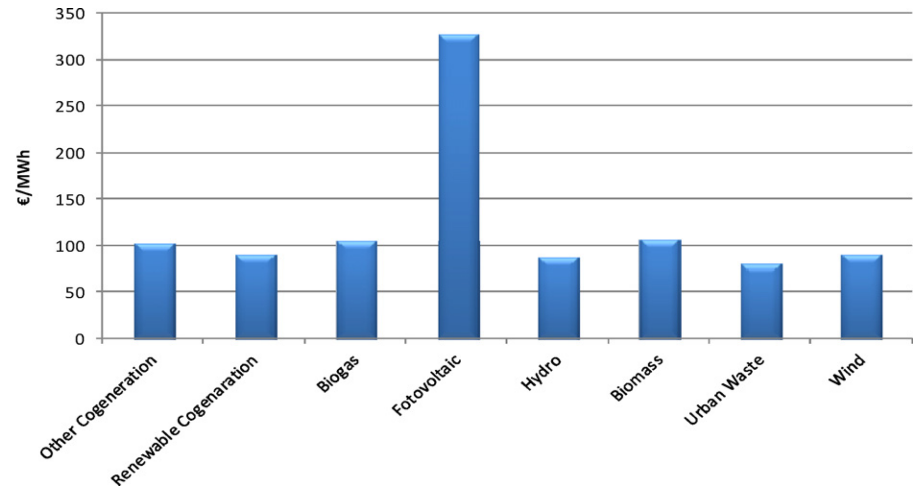


Fig. 17. Average price paid to the PREs by technology in January 2010 [16].

Table 6
Preliminary results for the estimated revenues.

Technology	Number of units	Total power capacity (MW)	Estimated €/MWh for feed-in tariff	Approx. years in the feed-in tariff	Estimated annual revenues (feed-in tariff)
StrafloMatrix	1	0.31	75.5	17	72,992 €
	2	0.62	74.7	22	111,722 €
	3	0.93	74.1	25	131,926 €
	4	1.24	73.7	25	139,092 €
VLH	1	0.39	76.9	12	128,897 €
	2	0.78	75.8	16	195,421 €
	3	1.16	74.9	20	228,457 €

The marginal increase of the electrical production rapidly decreases with the augmentation of number of installed units. This occurs because tailwater level rapidly increases with turbine discharge growth. The estimated annual energy production is always above the average target of 800 MWh/year, i.e. the annual average consumption of the electric fleet of the SMTUC.

Results shown in Tables 4 and 5 are indicative and must not be confused with those that can be performed using manufacturer's detailed data.

The feed-in tariff paid by the national grid to the special producers regime (independent small producers of renewable electric energy) is established by the Portuguese Government in the "Decreto-Lei n.° 225/2007" later corrected by the "Declaração de Rectificação n° 71/2007". The price of the hydroelectric production is calculated by a formula with three main terms defined as: fixed term, variable term and environmental term. These terms are multiplied by a modulation coefficient computed according to the peak and low electric production tariff periods. The feed-in revenue is monthly updated according to the inflation rate (computed excluding housing). The average electric energy prices, listed by technology type, paid to the special producers in January 2009, are presented in Fig. 17.

As it can be seen, the lowest average electric price is paid to the small hydropower producers, with 87.4 €/MWh, a low price when compared to photovoltaic that as a price of 338 €/MWh. The main reason for the difference is the so called *Z* factor, a multiplying value that reflects the characteristics of the resource and the technological maturity of the production process. The reduced feed-in tariff for small hydroelectric plants is one of the main explanations for the reduction in new investments, felt in the past years, besides the environmental administrative issues.

For small hydro power plants, special regime remuneration will end after 20 years (eventually extended to 5 extra years) or when a total amount of 52 GWh per MW of installed capacity is reach. After this period, the national grid will pay to the producers the price of the gross market of electric energy (actually about 50 €/MWh). The environmental component will be remunerated by green certificates.

The application of the feed-in tariff to the hydroelectric production presented in Tables 4 and 5 lead to the values presented in Table 6.

From Table 6 it can be seen that by increasing the number of units, the average price of the MWh is decreased, because the monthly average power will became lower (see Tables 4 and 5 for comparison of power capacity and estimated energy produced). However, by increasing the number of units the special feed-in tariff period is increased.

Preliminary calculations based on the value of the generated energy, also show that the project is economically viable.

4. Conclusions

The study showed the technical feasibility of the hydropower addition to the Coimbra dam-bridge, maintain its use as multi-purpose plant. The electricity produced is more than enough to supply the fleet of electric mini-buses and trolleys, allowing for the future expansion of this fleet.

Considering the solutions investigated it is clear at this stage that:

- The layout with the VLH units produces more energy comparatively to the StrafloMatrix units layout. However, the VLH units layout requires the radial gate removal, the installation of a upstream vertical lift gate and some demolition of the spillway sill.
- The layout with the StrafloMatrix units produces less energy but allows the preservation of the original radial gate.

The two low impact layouts are technically possible using the emerging technologies of very low head turbines that are already available in the market. These technologies have already been used with good technical results, in low head projects, However, because of the larger energy production and because is more fish-friendly, the VLH solutions appears to be the best choice.

Preliminary calculations based on the value of the generated energy, also show that the project is economically viable.

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